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Measurement errors in forest inventories and comparison of biomass estimation methods

Erros de medição em inventários florestais e comparação de métodos para estimar biomassa

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A B S T R A C T

Accurate quantification of above-ground biomass (AGB) in managed forests requires: consideration of inventory errors and the use of local or large-scale allometric models. In this study we focus on the measurement errors, data collection errors and we compared different methods to estimate AGB in managed tropical forest. The data were collected in 15 plots of 100 x 100 m. We evaluated the errors of the forest inventory of 8.898 trees. We used four methods to estimate AGB: three methods which use a pan-tropical equation, which depends on wood density data, with different ways of integrating the wood density data (obtained from dataset of the Brazilian Forest Service, Jari and Global Wood Density Database – GWDD); and one local equation. The main inventory errors were: problems with the same tree being identified as a different tree in consecutive measurements (16% of the trees). AGB estimates using each of the four methods were significantly different.

Keywords: rainforest management, forest inventory of companies, local and pan-tropical allometric models.

R E S U M O

A quantificação precisa da biomassa acima do solo (BAS) em florestas manejadas requer: consideração de erros de inventário e o uso de modelos alométricos locais ou de larga escala. Neste estudo, nos concentramos nos erros de medição, erros de coleta de dados e comparamos diferentes métodos para estimar a BAS em florestas tropicais manejadas. Os dados foram coletados em 15 parcelas de 100 x 100 m. Avaliou-se os erros do inventário florestal de 8.898 árvores. Foram utilizados quatro métodos para estimar a BAS: três métodos que utilizam uma equação pan-tropical, que depende de dados de densidade de madeira, com diferentes formas de integrar os dados de densidade da madeira (obtidos do banco de dados do Serviço Florestal Brasileiro, Jari e Global Wood Density Database). – GWDD); e uma equação local. Entre os principais erros de inventário, destacamos problemas com a mesma árvore sendo identificada como uma árvore diferente em medições consecutivas (16% das árvores). As estimativas de BAS utilizando cada um dos quatro métodos foram significativamente diferentes.

Palavras-chave: florestas tropicais manejadas, inventário florestal de empresas, modelos alométricos locais e pan-tropicais.

INTRODUCTION

Forest biomass and carbon stocks, as well as other ecosystem services can be impacted both positively and negatively by forest management. The short-term impacts vary according to the intensity of methods of logging and harvesting (West *et al*., 2014; Vidal *et al*., 2016). However, managed tropical forests represent an alternative between deforestation and full protection of the forest with the aim of maintenance of high biodiversity levels, carbon stocks and other environmental values even after exploitation (Putz *et al*., 2012).

Sustainable forest management aims to produce economic resources, social and ecological benefits continuously, respecting the support mechanisms of ecosystems (Gama *et al*., 2005; SFB, 2013). To ensure timber production and conservation of essential ecosystem services, such as the maintenance of carbon stocks from biomass, forest management needs to be effective on a regional scale (Imai *et al*., 2009; Rutishauser *et al*., 2015).

Moreover, estimating biomass from corporate forest inventories remains a challenge. However, uncertainties increase when working on large scales, demanding the development of new general allometric models and local validation of existing ones (Alvarez *et al*., 2012; Lima *et al*., 2012). The first challenge is related with the choice of the allometric equation and the availability of the data needed to fit in. The best-known general model to estimate biomass on a large scale is the one from Chave *et al*. (2005). These authors have consolidated a database of 2410 trees sampled in several tropical forests in the world, much from the Amazon, and generated equations with applicability in various regions within the pan-tropical zone. This forest biomass database comprised trees from 5 to 156 cm in diameter.

Dry above-ground biomass estimates using these pan-tropical equations have performed well in the Eastern Amazon (Lima, 2015). Indeed, Lima (2015) recommended the Chave *et al*. (2005) equation be used to estimate biomass in the Amazon region, due to its good fit and high concentration of trees sampled in this region. However, one potential barrier to the use of the Chave *et al*. (2005) equation is that it depends upon wood density data. Measurement of wood density requires obtaining samples which are not always possible, and the information available in the literature is poor for most species (Henry *et al*., 2010). The databases available on wood density in the Amazon are scarce and they do not cover the full range of tree species. Furthermore, the use of literature data creates the need for estimating the values of wood density of trees without identification.

The second challenge to improve biomass estimates in managed tropical forests are the possible problems associated with long-term monitoring, for example inventory data inconsistencies arising from forest management plans (FMP), data tabulation errors, differences in nomenclature and identification of species, and especially measurement errors of trees in the field, a frequent problem in management plans of large companies (Nogueira *et al*., 2005; Procópio and Secco, 2008; Lacerda and Nimmo, 2010).

The objectives of this study were to evaluate the errors and inconsistencies in the forest inventories and compare the different results of AGB (Mg ha^{-1}) estimated by four different methods using a local equation (which does not require wood density data) and a pan-tropical equation (which requires wood density data), and alternatives of determining wood density for unidentified trees species.

MATERIALS AND METHODS

Study area

The study was conducted on the forest management area (FMA) of the Jari Florestal Company, located in the municipality of Almerim, state of Pará, Brazil, between latitudes 0° 27′ and 1° 30′ S, and longitudes 51° 40′ and 53° 20′ W (Souza *et al*., 2014). The predominant vegetation in the study area is Sub Montane Dense Rain Forest (IBGE, 2012) and the predominant soils are yellow latosols and red-yellow ultisols.

Forest inventory data from permanent plots

We used the data from permanent plots of the Jari Florestal Company S.A. forest management area. These data were collected by an inventory team, before and after reduced impact logging (RIL), which began in 2003. The plots are 1 ha in size (100 m x 100 m) and are divided into 100 subplots of 10 m x 10 m. In each sub-plot, trees with diameter at breast height (DBH) 1.30 m above the ground greater than or equal to 10 cm are measured.

Inconsistencies were evaluated in 8898 trees of the forest inventory. During preliminary data analysis, trees with repeated measurements of DBH in the same occasion were excluded from the database, leaving only one observation referring to that individual.

Data analysis

The commercial volume (V, m^3) was calculated based on the diameter at breast height (DBH, cm) using the equation developed for dense forests in Amazonia by Nogueira *et al*. (2008):

$\ln(volume) = \alpha + \beta \times \ln(DBH)$ (Equation 1; Nogueira *et al*., 2008)

Where: α and β are -9.008 and 2.579 (R adjusted, $R^2aj = 0.96$; Residual standard error, RSE = 0.24) for trees <40 cm DBH and -6.860 and 1.994 for larger trees (R adjusted, $R^2aj = 0.80$; Residual standard error, RSE = 0.22).

The AGB calculation was performed only for live trees ≥ 10 cm of DBH, with inventory data before reduced impact logging. Trees with DBH data (but not full botanical identification) were considered as Not Identified (NI) but had their DBH values considered for the total biomass calculation of the plot. To estimate the AGB of each sampled tree and of the forest as a whole, we used one of Chave *et al*. (2005) allometric equations, and one of Lima (2015) local equations.

The estimate of aboveground biomass (AGB, Mg ha^{-1}) using the pan-tropical equation (Equation 2) is based on diameter at breast height (DBH, cm) and wood density (p, g cm^{-3}), as follows:

$$AGB = p \times e^{(-1.499 + 2.148 \times \ln(DBH) + 0,207 \times (\ln(DBH))^2 - 0.0281 \times (\ln(DBH))^3)}$$

(Equation 2; Chave *et al*., 2005), Multiple R-squared, $R^2 = 0.99$; Residual standard error, RSE = 0.35)

Wood density values were obtained from the databases of Jari Florestal SA, Global Wood Density Database (GWDD) – Chave *et al*. (2009), Zanne *et al*. (2009) and the Brazilian database, compiled by the Forest Products Laboratory of the Brazilian Forest Service. We organized and consolidated a list of genus occurring in the area and found in all three consulted data banks (Table 2). When we found more than one value per genus, the average wood density was used for according to the methodology used by Rutishauser *et al*. (2010) and Medjibe *et al*. (2011).

The estimate of dry aboveground biomass (DAGB, Mg ha^{-1}) using the local equation was calculated from a simple entry model, with diameter at breast height (DBH, cm) as the independent variable (Equation 3):

$\ln DAGB = -1.97256 + 2.44723 \times \ln DBH$ (Equation 3; Lima (2015); R adjusted, $R^2aj = 0.96$; Residual standard error, RSE = 0.437; F-statistic, F= 4958.94).

To compare the estimates of total biomass of the plots four methods were used to estimate biomass. They were defined depending on the calculation method and the form used to estimate the wood density of the species for which data were not available:

METHOD 1: Chave *et al*. (2005) equation, with Global wood density data (GWDD). For identified species without wood density and for the NI, we used the genus average and the overall average (p = 0.62) of the available timber densities, respectively.

METHOD 2: Chave *et al*. (2005) equation with average wood density of the three databases (GWDD, SFB and JARI). For individuals without wood density and for the NI, we used the Lima (2015) equation, which does not require wood density data.

METHOD 3: Lima (2015) equation for all individuals in the inventory.

METHOD 4: Chave *et al*. (2005) equation with average wood density of the three databases (GWDD, SFB and JARI), considering the large trees (DBH> 156 cm) as DBH = 156.

The diameter of 19 trees were higher than the diametric interval scope (DBH>156 cm) for the Chave *et al*. (2005) and Lima (2015) equations.

The biomass values for the trees above the diametric scope (DBH > 156 cm) of the equations were estimated by extrapolation (in Methods 1, Method 2 and Method 3) according to the methodology used by West *et al*. (2014).

For our study we assumed a maximum diameter growth of 2 cm yr^{-1}, based on the literature such as those reported by Braz *et al*. (2015) of 1.26 cm $year^{-1}$, and by Dauber *et al*. (2005) of 1.3 cm yr^{-1} for similar forest types in the Brazilian Amazon. When there were at least two measurements with consistent values for the same tree, the inconsistent values of negative growth and excessive positive growth were corrected by the average of the consistent growths. Only those individuals whose values were inconsistent in all measurements were eliminated from the database for the evaluation of the dynamics, maintaining the first measurement for biomass calculations.

The mean biomass value estimated using the four methods was calculated for the 15 plots. The four methods were compared by F test (n = 15) at the 5% error probability level and the confidence interval for the averages between the four methods was calculated. The statistical analyses were performed using the R programming language (R Development Core Team, 2015).

RESULTS AND DISCUSSION

Errors and inconsistencies in inventories

We identified four types of inconsistencies (Table 1) more recurrent in forest inventory data: 1) error in the nomenclature of species (NI); 2) measurement of negative DBH; 3) DBH growth measurement above 2 cm per year; and 4) lack of information on wood density.

The most frequently occurring inconsistency was related to the nomenclature of species, especially with the exchange of the common name of the same tree between measurements. This is due to difficulties in maintaining permanent and experienced teams in the field for carrying out the inventories and during the entry of field data to computers. Moreover, the lack of qualified professionals in the botanical identification service and the lack of collection of materials for identification can contribute to this type of error during corporate inventories.

Table 1 - Major inconsistencies in data from permanent plots of forest management monitoring inventories in the eastern Amazon (n = 8898)

Source of error	(NI)	G(-)	G>2cm	NºspN/D	NºtreeN/D
Quantity	1426	694	514	7	44
(%)	16.03	7.80	5.77	0.08	0.49

Nomenclature errors (NI), negative DBH growth (G -), positive growth of over 2 cm $year^{-1}$ (G>2cm), number of species without wood density data (Nºsp N/D) and number of trees without wood density data (NºtreeN/D).

The most common identification errors are: a) assigning different names for the same species; b) variation in the common names in different places; c) changes in species identification identified in previous measurements (Nogueira *et al*., 2005, Procópio and Secco, 2008; Lacerda and Nimmo, 2010). According to reports from the field teams, these errors occur due to fatigue caused by the great physical effort required to stay in the field for long and continued periods in the Jari Florestal's area. Lacerda and Nimmo (2010) emphasize that in the Brazilian Amazon, the most common method used to identify tree species in the field is using local people and local ecological knowledge.

Errors related to negative growth values can be explained by changes of the point of measurement. This is a common problem in corporate inventories where marking of the measurement spot on the trees is not a common practice. The same problem can occur for very high positive values, when a growth rate in diameter higher than expected for tropical forests is observed, because measurements are made below the level of the previous year.

Wood density for Eastern Amazon

In our database, 44 trees of seven species remained without a value for wood density and the wood density variation within the genus was high for some species (Supplementary Data), as in the case of the genus Aniba, which showed a variation of 0.37 to 1.05 g cm^{-3}.

The use of the genus average to estimate the density of the wood species that do not have information, as performed by Chave *et al*. (2005) and Medjibe *et al*. (2011) can be a source of error in the estimates of the biomass of trees. This type of error can be particularly observed in genera such as the

Swartzia, which have many species and a high variation, i.e. the variation of this genus in our study was 0.54 to 0.92 g cm^{-3}.

The most commonly used equations for estimating biomass stored in tropical forests depend on wood density, but this information is frequently not easy to obtain in the field. Most studies use information from the literature or a structured database. However, the databases are not always accessible to all potential users. The present study makes available information on wood density at the genus level for tropical forest species that occur in the eastern Amazon, systematized from three databanks (Supplementary Data).

Biomass estimates

The maximum diameter between plots ranged from 85.9 to 288.7 cm (Table 2), the number of large trees with a diameter ≥ 60 cm also varied considerably, from 3 to 27 trees.

The commercial volume per plot ranged from 196 to 554.2 m^3 ha^{-1}. Plots with a concentration of large trees and the majority of which had maximum DBHs, had larger volumes when compared to other assessments carried out in the same forest typology, 328.33 to 408.69 m^3 h^{-1} (Souza *et al*., 2006). The lower volume found in P-11 shows the importance of large trees for volume and biomass estimates in the forest, with few trees over 60 cm in diameter and no tree greater than 156 cm, indicating that most of the trees in the plot are thin, as identified in the studies of Mazzei *et al*. (2010), Medjibe et al. (2011), Sist *et al*. (2014) and West *et al*. (2014).

The estimated AGB calculated by Method 1 ranged from 234.5 to 936.59 Mg ha^{-1} among plots, with Method 2 from 217.02 to 881.11 Mg ha^{-1}, with Method 3 from 157.94 to 619.95 Mg ha^{-1} and with Method 4 from 217.01 to 716.69 Mg ha^{-1} (Table 3).

The average AGB estimated by Method 1 and Method 3 showed significant differences (F= 2.76, DF=13, p=0.05) based on their confidence intervals, showing that AGB estimates can be influenced according to the choice of approach (Figure 1). The equation which uses wood density as a predictive variable estimated higher AGB compared to that estimated by the local equation without wood density. The Methods 1, 2 and 4, based on DBH

Table 2 - Data on density of trees, maximum DBH, average DBH, number of large trees, species richness (Rsp) and volume (Vol) from the 15 plots of Jari Florestal Company

Plot	D (n.ha^{-1})	DBHmax (cm)	DBHm (cm)	Nº (≥60 cm)	Nº (≥156 cm)	R sp.	Vol (m^3 ha^{-1})
P-12	527	288.7	23.7	22	3	124	554.2
P-10	479	286.5	24.4	25	2	89	507
P-01	436	254.7	24.5	23	3	123	466.3
P-08	430	251.5	21.9	7	5	104	396.2
P-14	465	231.4	23.5	15	3	126	412.4
P-05	567	189.5	24.3	21	2	127	521.4
P-06	435	173.8	24.9	19	1	110	397.5
P-15	562	134.9	22.5	20	–	136	385.4
P-02	513	127.3	22.2	12	–	160	313.5
P-13	593	122.6	20.1	5	–	109	264.7
P-03	527	121.9	23.3	27	–	118	396.8
P-07	464	114.6	23.7	19	–	105	337.8
P-04	509	106.7	23.3	15	–	87	336.3
P-11	414	102.2	19.7	9	–	106	196
P-09	581	85.9	19.9	3	–	104	247.5
(15ha)	7502	–	–	242	19	–	5733
Average	500	172.8	22.8	16	3	115	382.2

Data on density of trees (D), maximum DBH (DBHmax), average DBH (DBHm), number of large trees (Nº), species richness (Rsp) and commercial volume (Vol).

Table 3 - Above-ground biomass (AGB, Mg ha^{-1}) and commercial volume (Vol,m^3 ha^{-1}) per plot, total and average (IC 95%), calculated by four different Methods

Plot	AGB1*	AGB2*	AGB3*	AGB4*	Vol
P-01	736.74	701.33	496.82	573.45	466.3
P-02	363.36	348.80	259.74	383.95	313.5
P-03	508.53	487.78	343.15	487.80	396.8
P-04	390.69	369.68	269.60	369.68	336.3
P-05	749.77	728.86	492.42	700.97	521.4
P-06	544.10	528.84	360.21	517.42	397.5
P-07	403.96	389.57	274.06	389.57	337.8
P-08	681.31	618.26	466.74	435.23	396.2
P-09	277.69	273.21	189.05	273.23	247.5
P-10	749.41	708.62	548.21	520.80	507
P-11	234.50	216.97	157.94	217.02	196
P-12	936.59	885.68	619.95	716.69	554.2
P-13	290.85	297.93	209.25	297.94	264.7
P-14	613.43	577.86	417.86	487.72	412.4
P-15	483.20	467.79	332.48	467.79	385.4
Total	7964.13	7601.20	5437.49	6839.26	5733
Average IC (95%)	530.94± 115.46	505.87 ± 107.25	362.49± 77.39	455.95± 79	382.2± 57

*Above-ground biomass (AGB) estimated by Method 1 (AGB1), AGB estimated by Method 2 (AGB2), AGB estimated by Method 3 (AGB3) and AGB estimated by Method 4 (AGB4).

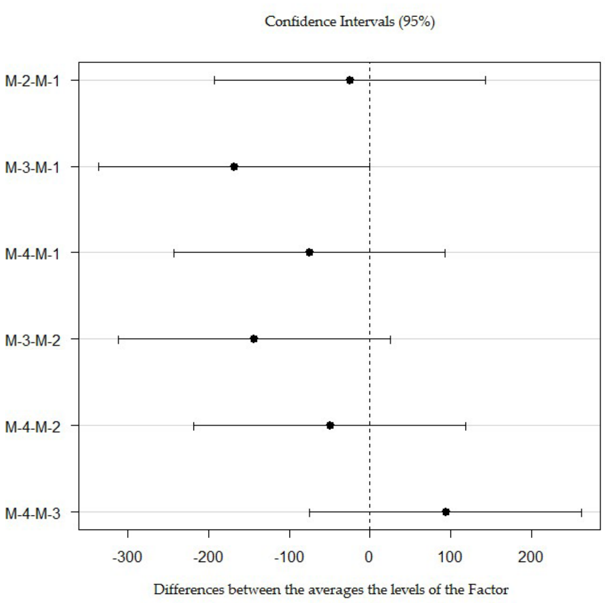

Figure 1 - Confidence intervals of the means for the four Methods (Method 1 (M-1), Method 2 (M-2), Method 3 (M-3) and Method 4 (M-4)) proposed to calculate AGB of the 15 permanent plots of Jari Florestal Company.

and wood density, showed greater variation in estimates due to the need to also estimate some wood density data. The Method 3 which does not depend on this variable had the lowest variation.

Some authors (i.e. Medjibe *et al*., 2011; Sist *et al*., 2014) prefer to replace DBHs of larger individuals by the maximum scope DBH. In our study, we did this substitution in Method 4, which resulted in 14% reduction in the estimated average biomass. These data show the importance of these large trees for biomass estimates in sites with many trees of this size, such as the Jari Florestal area.

Biomass estimates using Method 1, Method 2 and Method 4 (based on the global equation and the wood density) were quite high in relation to some estimates of biomass in the Amazon. In Central Amazon, Lima *et al*. (2012) estimated 253 Mg ha^{-1}. In Eastern Amazon, Mazzei *et al*. (2010) found an average of 409.8 Mg ha^{-1}, in the same region Sist *et al*. (2014) found 378 Mg ha^{-1}, West *et al*. (2014) estimated 260 Mg ha^{-1} and Vidal *et al*. (2016) estimated around 237 Mg ha^{-1}.

The calculation of the AGB using Method 3 proved to be more conservative relative to the other methods because it is a local model based on a single input variable (i.e. DBH). Another indication that this method may be more reliable is that it was the only one to estimate the biomass below the commercial volume. Biomass estimates greater than the volumes (i.e. Method 1, Method 2 and Method 4) imply a predominance of wood densities greater than 1 Mg m^{-3}, and this would not be consistent with the density values of most species (Supplementary Data).

CONCLUSIONS

The nomenclature inconsistencies and species identification were preponderant for AGB determination, analyzes indicated that the errors and inconsistencies of forest business inventories may compromise the quality of AGB estimates. The possible solutions to the studied problem are the promotion of knowledge about the diversity of forest species in the region and the increase of efforts in the modelling works in the Amazon biome.

We suggest the use of local allometric models (a model based on DBH only and without wood density data) in situations where the information for wood density is scarce, especially when there is not the correct identification of some forest species.

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